GRAIL refinements to lunar seismic structure

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The present-day internal structure of the Moon provides insight not only into its own formation and evolution, but also that of all rocky planetary bodies. The most direct way to probe a planet's interior structure is through seismology. As part of the Apollo lunar missions, four seismometers were deployed on the nearside surface of the Moon between the years 1969 and 1972. These instruments operated continuously until 1977, forming the only substantial extraterrestrial seismic data set in existence. These data have been used to constrain various aspects of the seismic velocity and density structure of the Moon. Typical 1-D models recognize a 30-60 km thick crust overlying a nearly constant-velocity mantle, and extend to a depth of approximately 1000 km, below which the lack of penetrating moonquake ray-paths precludes the seismic determination of deeper structure.

Previously, the lack of observed moonquakes from the far side of the Moon has been used to infer the presence of a highly attenuating (possibly molten) core. Indirect geophysical measurements such as moment of inertia, magnetic induction, lunar laser ranging, and elemental abundances of mare basalts also place varying constraints on core size and state. In combination with seismic studies, these indirect measurements have been used to arrive at a commonly accepted model of the Moon's deepest interior that includes a solid inner and fluid outer core, overlain by a partial melt boundary layer.

We recently applied modern array seismology techniques to the Apollo data and revealed detailed core structure, including the first direct confirmation of the presence of a solid inner core. Our study focused on the identification of core-reflected phases in deep moonquake seismograms. The resulting model of the Moon's innermost structure was found to be consistent with the commonly accepted model. However, the modeled layer radii may vary by tens of kilometers, as is expected when accounting for uncertainties such as moonquake location, timing errors, and potential seismic heterogeneities. In addition, the modeled velocities may vary with a 1-to-1 trade-off with the modeled reflector depth.

The GRAIL (Gravity Recovery and Interior Laboratory) mission, launched in Sept. 2011, placed two nearly identical spacecraft in lunar orbit. The two satellites make extremely high-resolution measurements of the lunar gravity field, which can be used to constrain the interior structure of the Moon using a "crust to core" approach. GRAIL's constraints on crustal thickness, mantle structure, core radius and stratification, and core state (solid vs. molten) will complement seismic investigations in several ways.

Here we present a progress report on our efforts to advance our knowledge of the Moon's internal structure using joint gravity and seismic analyses. We will focus on methodology, including 1) refinements to the seismic core constraint accomplished through array processing of Apollo seismic data, made by applying a set of travel time corrections based on GRAIL structure estimates local to each Apollo seismic station; 2) modeling deep lunar structure through synthetic seismograms, to test whether the seismic core model can reproduce the core reflections observed in the Apollo seismograms; and 3) a joint seismic and gravity inversion in which we attempt to fit a family of seismic structure models with the gravity constraints from GRAIL, resulting in maps of seismic velocities and densities that vary from a nominal model both laterally and with depth.